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1979

CALIFORNIA DIVISION OF MINES AND GEOLOGY

SPECIAL REPORT 136

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SPECIAL REPORT 136

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PART I: WRIGHT MOUNTAIN LANDSLIDE: RENEWED MOVEMENT IN 1967

By
D.M. Morton and M.P. Kennedy

PART II: WRIGHT MOUNTAIN MUDFLOWS: SPRING 1969

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D.M. Morton, R.H. Campbell, A.G. Barrows, Jr.,
J.E. Kahle, and R.F. Yerkes

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ABSTRACT

Wright Mountain landslide, located above the mountain community of Wrightwood, formed prior to the year 1500. Subsequent dissection of the landslide has resulted in intermittent landsliding. Part of the landsliding was renewed movement of a major part of the 1967 and 1968 composite landslide. As a result, about one million cubic yards of loose debris from the renewed landsliding flowed into the steep upper reaches of Heath Canyon which cuts Wright Mountain landslide. The quantity of loose landslide debris is adequate to produce several periods of mudflow activity on the same order of magnitude as those of 1941 and 1965, which inundated parts of the community of Wrightwood. The addition of sufficient water, in the form of snowmelt or rain, to the landslide debris is all that is necessary to produce mudflows.

Water from rapid melting of a heavy winter snowpack combined with debris to form mudflows over a 40–day period during May and June of 1969. Observations made over this period indicate three distinct mudflow stages which constitute a spring mudflow cycle for the area. The initial, or waxing, stage consisted of mudflows of short duration which aggraded the lower alluviated canyon floor of Heath Creek, the upper part of which was the point of origin of the mudflows. The second, or climactic, stage was characterized by more frequent and larger mudflows, incision of a single, narrow, U–shaped channel in the alluviated canyon floor, and transportation of debris in flows two miles from their point of origin. The third, or waning, stage, characterized by a decrease in meltwater supply, consisted of short–duration flows which backfilled the previously cut channel, again aggrading the alluviated canyon floor.

Mudflow velocities ranged from two to 12.5 feet per second, and they recurred each 0.5 to 35 minutes during the climactic stage. The 1969 flows deposited an estimated 100,000 cubic yards of debris.

Forty mudflow and water samples were collected at two sampling sites, one about 1,800 feet downstream and the other 6,900 feet downstream from the area of origin of the flows. Coarse mudflow material consisted of 44 to 75 percent rock by volume and ranged in specific gravity from 1.72 to 2.23. Samples from the site nearer the origin of the mudflows had a range in sorting index of 3.4 to 4.2; the range was 4.8 to 5.2 at the lower site.

The 1969 mudflows removed only a small part of the debris in Heath Creek Canyon bottom. Sufficient debris remains for a number of future periods of mudflow on the order of those of 1941 or 1969.

ACKNOWLEDGMENTS

B.W. Troxel, California Division of Mines and Geology, R.H. Jahns, Stanford University, and A.O. Woodford, Pomona College, critically read an early version of Part I of this paper. R.H. Campbell of the U.S. Geological Survey critically reviewed the entire paper.

Mr. James R. Townsend, Geologist, Foundation and Materials Branch, U.S. Army Engineer District, Los Angeles, kindly supplied data on pre–mudflow snow depth and entrained air content of mudflow samples, and provided helicopter transport to Wright Mountain in March 1969 and during the peak of the mudflow activity. A number of individuals were helpful in collecting data during the 1969 flows. We appreciate the communicated observations of K. Barrows, J. Buchanan, D. Crandell, H. Eagle, H. Smedes, B. Troxel, C. Wentworth, and J. Ziony. Mr. Clark H. Gleason, Forester, U.S. Forest Service, kindly made available an unpublished report on the 1941 mudflows. Sieve analysis and related work was performed in the Geology Department, Seaver Laboratory, Pomona College; the generous hospitality of Pomona College is appreciated.

PART I. WRIGHT MOUNTAIN LANDSLIDE: RENEWED MOVEMENT IN 1967

By D.M. Morton[1] and M.P. Kennedy[2]

INTRODUCTION

The Wright Mountain landslide has been intermittently active for 450 years. This minimum age was obtained from tree ring counts made of living conifers (*Pinus jefferyi*) on the lower part of the landslide. The landslide is the result of over–steepening produced by fluvial erosion and presently exhibits a large area of barren scars and a number of small forests with trees tipped topsy–turvy. North–flowing Heath Canyon drains the landslide area. Landslide debris from the canyon floor is transported down the canyon chiefly by mudflows and is deposited as a fan at the canyon mouth. The community of Wrightwood was built on this fan and, in 1941 and 1965, mudflows inundated streets and residences there. Recent activity has increased the debris available for mudflows and has thus increased the hazard to the community.

The well–known mudflows of 1941 and the attendant problems of Wrightwood are documented (Gleason and Amidon, 1941; Sharp and Nobles, 1953). The present investigation concentrated on the significance of Wright Mountain landslide and the renewed movement where mudflows have originated.

In the late fall of 1966, upper Heath Canyon was occupied by a composite landslide of about 500,000 square yards containing 18 million cubic yards of debris; there was no evidence of movement. In June 1967, material in the central part of the landslide showed fresh slump scarps, and an initially intact block in the uppermost part of the landslide, about 500 × 900 feet in plan, had dropped about one foot. This reportedly took place within a few weeks in May. A planimetric map of the active block was made and the rate of its movement was measured by repeated plane–table and tape surveys.

GEOLOGIC SETTING AND GENERAL FEATURES

The Wright Mountain landslide has its head on the north side of Wright Mountain, a topographic prominence on Blue Ridge which trends southeast between the San Andreas and the Punchbowl fault zones (figure 1). Bedrock in the Wright Mountain area is Pelona Schist, characterized here by the abundance of white mica and albite. The schistosity dips relatively uniformly southward into the north slope of Blue Ridge. Much of the schist is moderately to intensely fractured, probably as a result of movements along the nearby fault zones. The fractured and fissile schist fails readily. Many of the canyons adjacent to Heath Canyon contain landslide deposits of various sizes (Morton and Streitz, 1969).

EVOLUTION

The Wright Mountain landslide originated through large–scale slumping at the head of Heath Canyon with movement principally downslope to the north and west. Rotational movements produced large slump blocks; the closed depressions formed by the rotational movement filled with sediment, resulting in relatively flat surfaces on the landslide deposit. The lower end of the landslide today is marked by a bedrock "narrows" (or gap) which, although not clearly resolved, appears to be the breached lower end of a ridge extending into the canyon from the west. The pre–landslide channel was farther to the east. The landslide deposit probably blocked the old channel and post–landslide channel–cutting resulted in a superposed drainage.

After the formation of the landslide deposit, a V–shaped canyon was eroded headward up Heath Canyon through the toe of the deposit. Fluvial erosion was accompanied by lateral and headward slumping directly proportional to the canyon size. Because this canyon development was generally west of the canyon buried by the landslide, slopes to the west not initially involved in the Wright Mountain landslide were over-steepened and additional landslides resulted. Until 1929, the scarp area of the Wright Mountain landslide had not been reached by the canyon development. In the late 1930's, however, erosion cut headward into the base of the scarp, and by 1941 headward slumping had reached the top of the scarp (Gleason and Amidon, 1941). There were apparently only minor movements between the summer of 1941 and the early spring of 1967.

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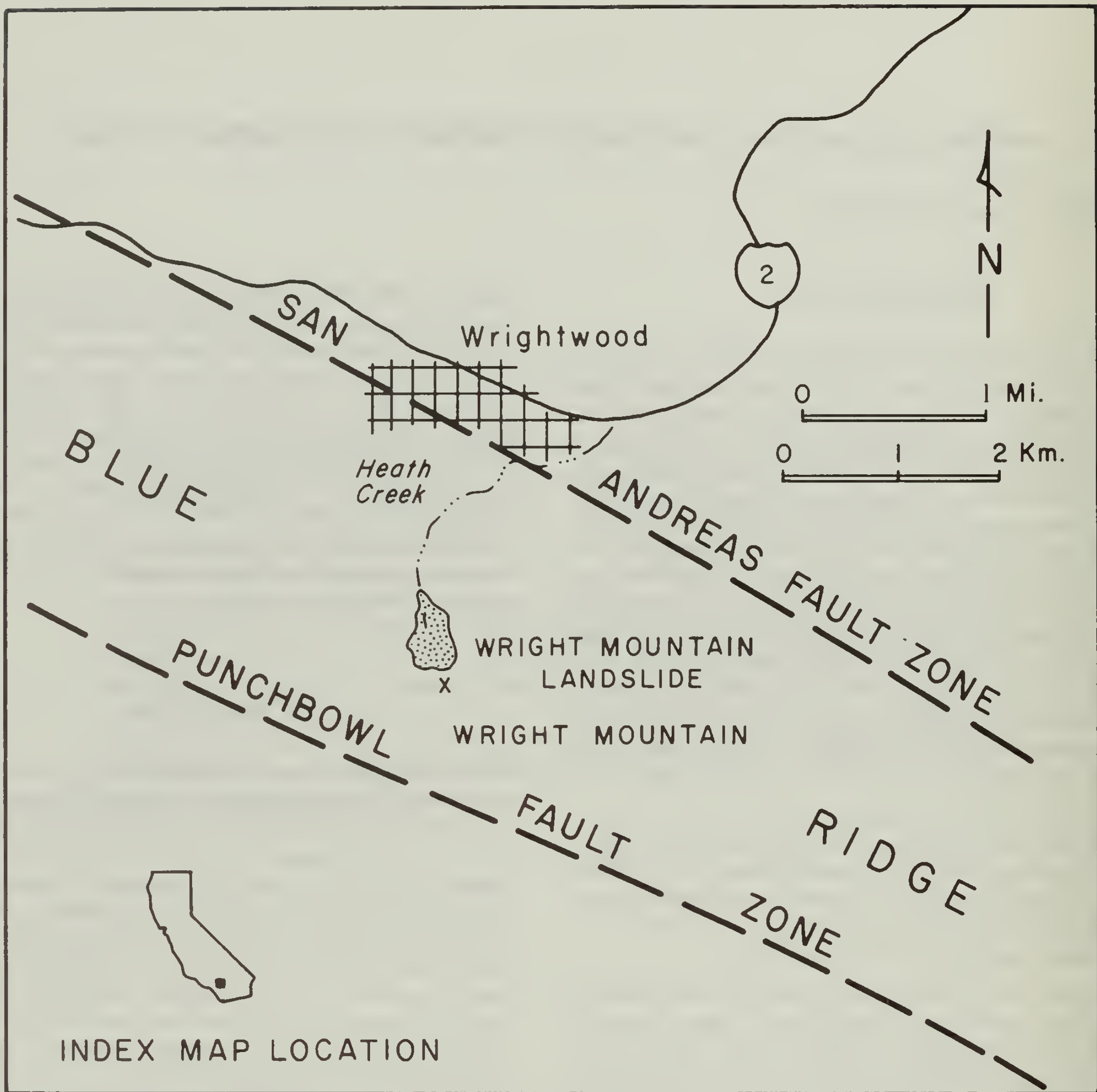

Figure 1. Index map showing location of Wrightwood.

The volume of the landslide deposit within Heath Canyon is approximately 18 million cubic yards, assuming an average 100-foot thickness of the debris. A similar figure is obtained by construction of longitudinal sections through the landslide.

RENEWED LANDSLIDE MOVEMENT

South of the rim of the scarp along the top of Wright Mountain are at least four north-facing landslide scarps 1 to 5 feet high; the most pronounced of the four shows on the 1929 aerial photographs. These scarps do not appear to have moved between 1929 and 1967, as the 1966 visit showed them to be slightly modified by erosion and covered by a thin layer of plant debris. In the spring of 1967, however, movement began on what was then the northernmost scarp (figure 2).

On June 16, 1967, recent displacement amounted to about 18 inches on the northernmost scarp, which was then about 300 feet long. On June 20, new scarps were noted in a forested area. These did not appear to have been pre-determined by older scarps. By late September the active scarps had joined to form a single continuous scarp approximately 900 feet long, with a maximum scarp height* of 26 feet (figure 2). Also at this time, the flanks of the moving block were marked for the first time by low scarps. Using the planimetric map and estimated thickness of the active block, the

* Scarp height as used herein is the distance between the top and bottom of the scarp measured in the plane of the scarp normal to the strike of the scarp.

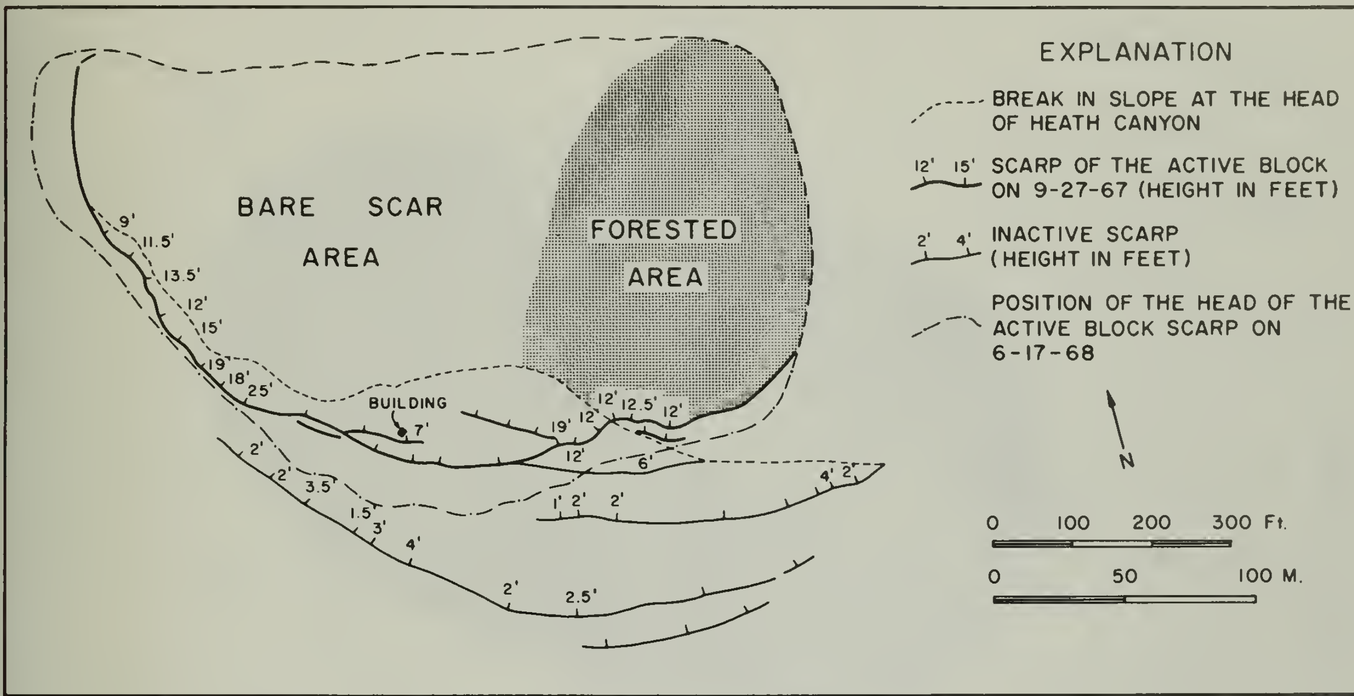

Figure 2. Planimetric map of the active block within the southwest corner of the Wright Mountain landslide.

volume of the block is estimated to be one million cubic yards.

From June through August of 1967, downward movement of the block was essentially constant at a rate of about an inch a day. By September, movement had accelerated to 5 inches a day. From September 30 to October 6, measurements every two days indicated that movement was accelerating at a rate of about 0.2 inch per day. The mean scarp height increase for the following week was 17 inches per day, reaching a maximum rate of movement in excess of 2 feet per day by mid-October. Subsequent deceleration was rapid, and by the beginning of November the movement had all but stopped. Measurement on June 17, 1968, of a building that rode the moving block down, showed that it had moved 150 feet since June 16, 1967 (figure 3). More accurate measurement of total displacement, based on scarp height, was precluded by the slumping of the main scarp, which began to fail in October 1967. Measurements on June 17, 1968, revealed that the head of the scarp had retreated 20 to 100 feet south of its position on September 27, 1967.

The surface in the center of the block (general area of building on figure 4) remained horizontal throughout the movement. Backward rotational movement, however, was pronounced during the later part of the period of landsliding, especially in the western and eastern parts of the block. The dip of the scarp was 65° to 75° north. Slickensides in the center of the scarp were directly down dip. On the western side, the slickensides had a trend 10° to 15° west of the dip, and on the eastern side there was a similar trend to the east. There was little evidence of the flanks (lateral margins) of the block until late September, when the main scarp had reached a height of 26 feet. Until then the movement expressed by the ever-increasing scarp height was taken up within the block itself, with no expression of movement along what later were clearly the lateral limits and toe of the block. Throughout most of the summer some sloughing continued below the western part of the main scarp, but there was no apparent relation between the rates and geometry of that sloughing and the rates and geometry of the movement of the block.

The position of the toe became evident in the central and eastern parts of the block on September 28, 1967. From then until mid-October, the period of most rapid displacement, the toe rode out over a near-vertical cliff on a nearly horizontal plane, where the material sloughed off and tumbled down to the floor of Heath Canyon. This debris was carried as far as 1,000 feet from the toe.

SIGNIFICANCE OF THE RENEWED MOVEMENT

Between June 1967 and June 1968 a block with an estimated volume of one million cubic yards moved 150 feet in what may be the largest single failure on the Wright Mountain landslide in nearly fifty years. The failure of a block this large must be considered a major event in the erosion of the Wright Mountain

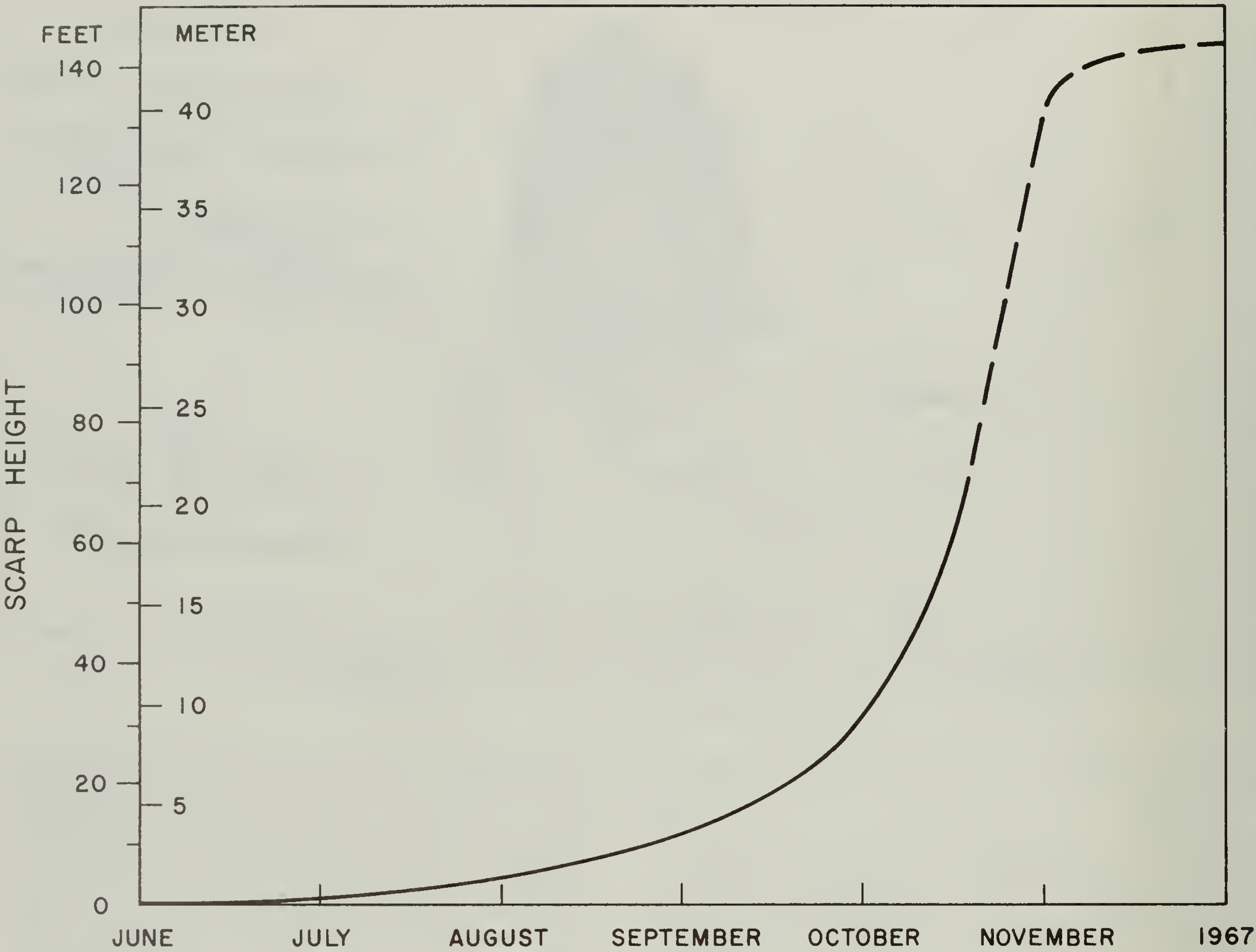

Figure 3. Diagrammatic representation of the rate of landslide movement between June and December 1967 as expressed by increase in scarp height.

landslide. Three important consequences of this failure are evident:

(1) An area that has been immune to high erosion rates since at least 1929 (the forested area of figure 2) is now vulnerable to an accelerated erosion that will result in an increased production of debris for Heath Canyon until about 1980.

(2) A large, new deposit of loose debris now rests where it can be carried down and out of Heath Canyon by mudflows.

(3) Blocks on the south side of the failure, which are bounded by old low landslide scarps, are much more susceptible to failure now that they lack the support of the block that failed.

The addition of approximately one million cubic yards of debris to the canyon bottom is a matter of great practical concern to the residents of Wrightwood. Water is all that is needed to turn this debris into mudflows that could inundate streets and residences in Wrightwood.

Mudflows could occur after a period of exceptionally warm weather in late spring when the winter snowpack melts rapidly. Or they could occur in the summer or early fall as the result of a rainfall of high intensity and short duration ("cloudburst"). They could occur, too, during the "normal" rainy season of late fall and winter as the result of a rainfall of long duration (this was the origin of the 1965 mudflow that inundated 19 homes on the alluvial fan of Heath Canyon).

4A

4B

Figure 4. View looking southwest across the head of Heath Creek Canyon. Figure 4A was taken in June 1967, prior to failure of the active block. Figure 4B was taken in November 1967, after failure of the active block.

PART II: WRIGHT MOUNTAIN MUDFLOW: SPRING 1969

By D.M. Morton[1], R.H. Campbell[2], A.G. Barrows, Jr.[3], J.E. Kahle[3], and R.F. Yerkes[2]

INTRODUCTION

In May and June of 1969, mudflows were observed in Heath Creek over a 40–day period during the thaw of the snowpack from the exceptionally wet 1968–69 winter. Observations of the 1969 mudflows are summarized here.

HEATH CANYON DRAINAGE

Branching headwater tributaries of Heath Creek drain the head and steep upper slopes of the active parts of the landslide (figure 5). The trunk drainage of Heath Creek is incised to bedrock in the lower part of the steep slopes of the landslide toe area, forming a *bedrock chute* with a gradient of 31 degrees between elevations of 7,000 and 7,500 feet. At the foot of the bedrock chute, the gradient abruptly decreases to 17 degrees, and downstream the bottom of the canyon is filled with alluvium. This *alluviated canyon* reach extends 3/4 mile downstream to the apex of Heath Canyon fan at an elevation of 6,500 feet. From the relatively steep upper end the gradient decreases gradually to 7 degrees at the lower end. The "narrows" discussed earlier is located about midway through this reach and was used as a landmark by Sharp and Nobles (1953). Streamflow at the apex of the fan is funneled by a flood control levee into a man–made channel along the east side of the fan. This *controlled channel* extends 1/2 mile downstream to a point where the gradient decreases to 5 degrees. There, near the confluence of the fans from Heath and Sheep Canyons, the flood control levee swings away from the hillside, leaving a broad area with a low gradient where mudflow deposition is encouraged. The principal area of deposition for the climactic stage of the 1969 mudflows was in this controlled depositional reach.

Downstream, beyond the area of principal deposition across the more densely built–up lower third of the fan, the drainage is again confined to a narrow man–made channel between levees. These levees end where northerly–flowing Heath Creek joins Swarthout Creek. About 1/4 mile downstream from the Heath Creek–Swarthout Creek confluence, the combined flow joins Sheep Creek, turns north, and drains to the closed basin of Mirage Lake (dry) 13 miles to the north in the Mojave Desert. Only a small volume of sandy mud was deposited below the confluence of Swarthout and Heath Creeks during 1969. Investigation of the 1969 spring mudflow cycle was confined to the area above the junction of Heath Creek and Swarthout Creek.

Troxel and Gunderson (1970) noted the presence at Mirage Lake of fragments of rocks similar to those in Wright Mountain. Troxel (oral communication, 1976) believes that the rock fragments, some as large as 6 inches in diameter, were transported in mudflows, and that Mirage Lake may have formed behind a dam created by an ancient mudflow from the Wright Mountain area.

SAMPLE SITES

The upper of two sample sites (figure 6) was about 200 feet upstream from the "narrows" in the alluviated canyon reach. The lower sample site was about 200 feet upstream from the conjunction of the controlled channel with the controlled depositional reach.

1969 MUDFLOW CYCLE

A deep snowpack developed during the winter of 1968–69. Snow depth on Wright Mountain, measured on March 3, 1969 (figure 7), ranged between 68 and 104 inches with an equivalent water content of 26 to 45 inches (J.R. Townsend, personal communication, 1969). Thus, early in the spring of 1969 upper Heath Canyon contained abundant debris and an adequate source of water for spring mudflows.

Around the first of May, 1969, steady thaw of the snowpack began as mean daily temperatures stayed above freezing. This was followed by a 40–day period of mudflow activity that can be conveniently described as consisting of three stages: (1) waxing, (2) climactic, and (3) waning. This spring mudflow cycle

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Figure 5. View looking east across the profile of the active block. Figure 5A was taken on September 27, 1967, when the toe of the active block first became apparent. Figure 5B was taken in August 1968, after failure of the active block. Circled pine tree trunk shows the magnitude of the vertical displacement.

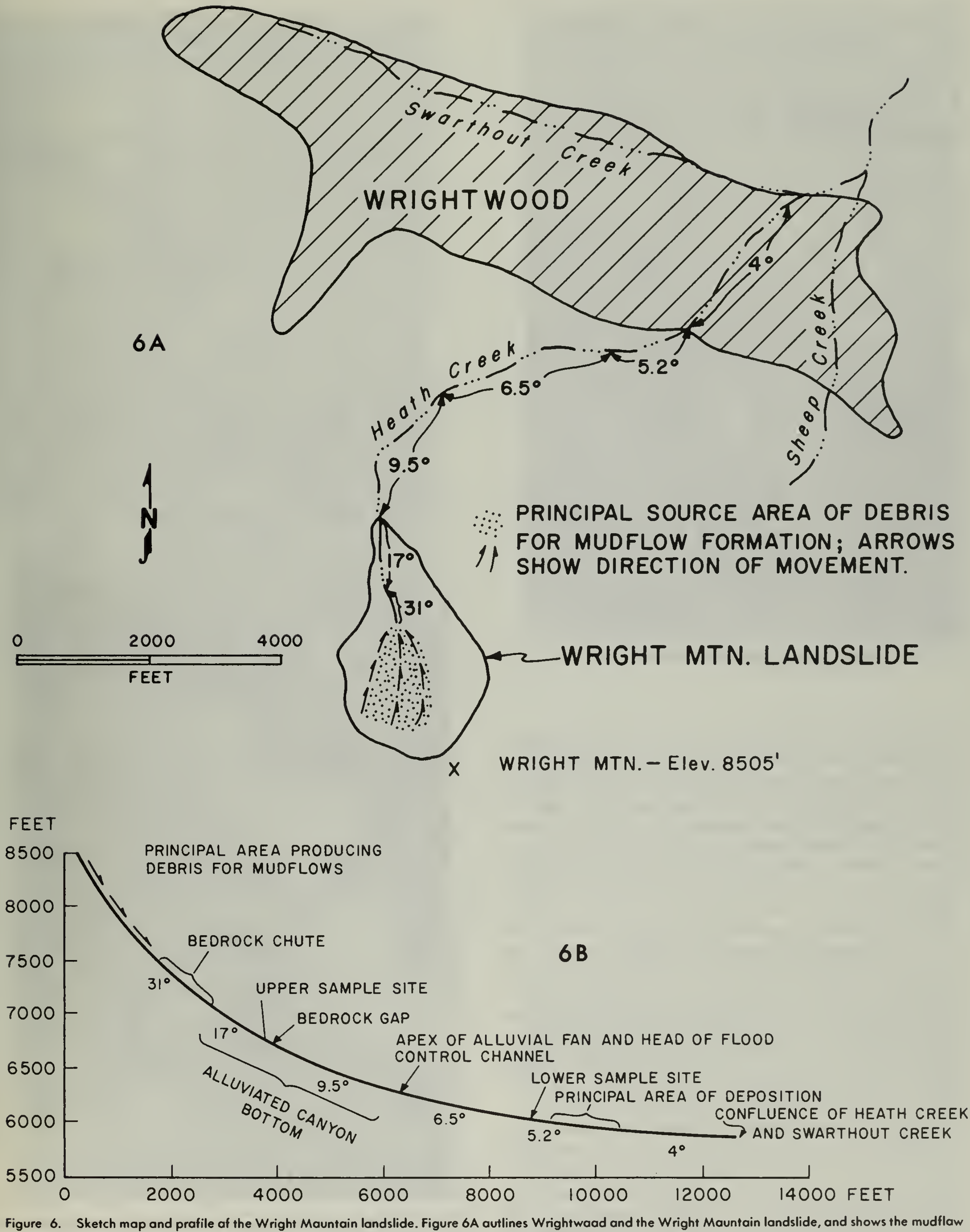

Figure 6. Sketch map and profile of the Wright Mountain landslide. Figure 6A outlines Wrightwood and the Wright Mountain landslide, and shows the mudflow course, with gradients, along with the principal source area of debris for the 1969 mudflows. Figure 6B profiles the Wright Mountain landslide, showing mudflow gradients and sample sites.

Figure 7. Wright Mountain Landslide, March 1969.

is probably typical of the events that will recur in the area whenever an appreciable snowpack thaws.

Waxing Stage. The waxing stage of the mudflow cycle consisted of short–duration mudflows that deposited debris in the alluviated canyon bottom above the apex of Heath Canyon fan. For the first five days of mudflow activity (to May 4), mudflows arriving at the "narrows" were dammed by a snow avalanche deposit (figure 8). An estimated 3,000 cubic yards of mudflow debris accumulated behind this dam, reaching a thickness of at least 15 feet. The snow dam was breached on May 5th, and for the following 11 days mudflows passed through it and deposited their debris in a braided fashion farther down the alluviated canyon bottom to the apex of the fan. Meanwhile, a U–shaped channel was incised into the deposits behind the breached dam in the reach above the "narrows" and a few flows passed the apex of the fan.

Climactic Stage. More prolonged mudflows began on May 17, and the production of the largest mudflows and/or the longest in duration continued for the following six days. During this period, mudflows originated at progressively higher elevations in the upper reaches of Heath Canyon. During the first two or three days, the incision of the narrow U–shaped channel was extended downstream through the alluviated canyon (figure 9) from the bedrock gap to the apex of the fan, where the mudflows entered the man–made flood control channel. Subsequent mudflows travelled through the entire length of the alluviated canyon reach in this U–shaped channel, as well as across the apex and upper part of the fan in the man–made flood control channel, without observable net deposition or erosion. Deposition took place chiefly on the middle and lower parts of Heath Canyon fan and was limited by flood control levees on the east side of the fan. A few of the larger flows deposited debris as far downstream as the confluence of Heath and Swarthout Creeks at the toe of the fan, 2 miles from their point of origin.

Waning Stage. About May 22, mudflows began to steadily decrease in volume, frequency, and duration. A marked decrease in meltwater supply reflected a daily reduction in the area covered by snow until only remnants of thicker drifts in shade remained. Progressively smaller mudflows gradually backfilled the U–shaped channel through the full length of the alluviated canyon (figure 10). Subsequent mudflows spilled over the backfilled channel and once again aggraded

Figure 8. View up alluviated canyon bottom (17°) reach during the waxing stage. Debris for mudflows at this time (May 5, 1969) is in the area immediately below the clouds.

Figure 9. Same view as figure 8 taken on May 18, 1969 after a single mudflow channel has been cut (approximately 12 feet depth) during climactic stage.

Figure 10. Same view as figure 8, taken during the waning stage of the mudflow cycle after most of the deep channel had been filled.

the surface of the fan apex and the canyon. By June 6, the snow pack had essentially disappeared and mudflows due to meltwater had ceased for the season.

MUDFLOW INCEPTION

With the advent of a steady thaw, a continuous supply of meltwater percolated into the landslide mass beneath the snow cover. Soon the landslide mass became saturated, and there was sufficient surface runoff to form small streams. Nearly all the meltwater, however, was quickly absorbed by debris with little excess available to contribute to stream flow. At no time was there surface runoff of *water* of more than a few gallons per minute. The meltwater permeated into the debris, filling the established drainage channels, particularly in the bedrock chute, and aided in the mobilization of the channel–fill debris into episodic mudflows. These flows tended to flush the drainage channels until bare bedrock was exposed. Meltwater also percolated through the landslide mass toward steep faces above the drainage channels in the toe area of the landslide. Saturated debris at these steep faces was continuously calved by relatively small, shallow slumps, slides and flows. This activity constantly replenished the supply of debris in the channels. In a number of cases the debris contained sufficient water to continue moving down the drainage channels without interruption. In other cases, slumping debris accumulated in the channels until a discrete body of debris ("slug") absorbed sufficient water to remobilize.

MUDFLOW CHARACTERISTICS

Mobilized debris moved down the bedrock chute as individual slugs, cascading over waterfalls before entering the alluviated canyon bottom. At the upper end of the alluviated canyon, the debris was momentarily out of sight in a chasm cut deeply into a massive bank of drifted and avalanche–deposited snow. The debris appeared thoroughly mixed where it disappeared from view. When next visible, the mudflows had blunt, rocky snouts, generally 3 to 4 feet high (figures 11, 12). These snouts consisted of relatively well–sorted clasts, generally 5 inches to 2 feet in diameter, with occasional clasts as large as 4 feet in diameter. Behind this coarse, bouldery front was a mixture of unsorted

Figure 11. Neor verticol ongle view of rock front of mudflow immediotely obove bedrock gop. Note the well–sorted noture of the rocks (lorger ones two feet in diometer) constituting the front, ond olso the opporent decreose in clost size ond the progressive increose in mud content behind the front.

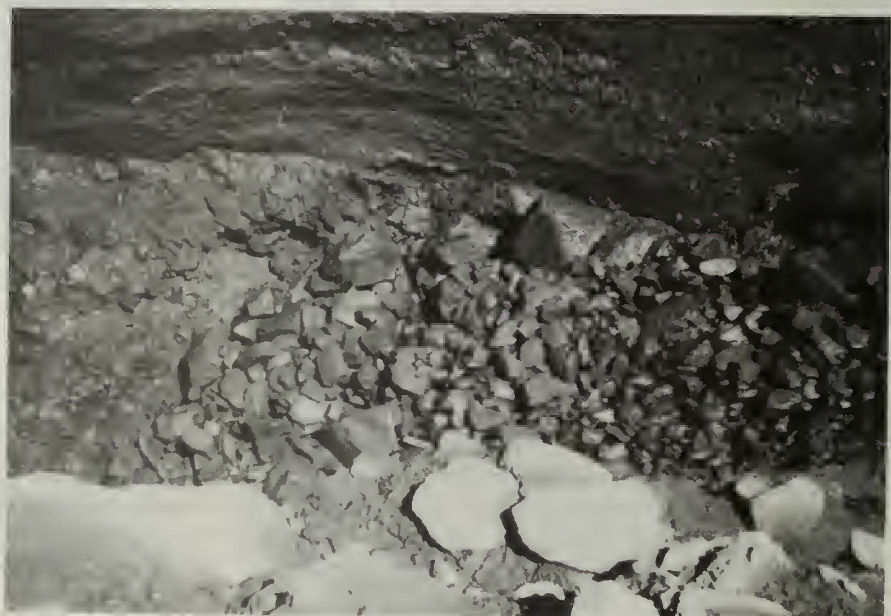

Figure 12. Verticol view of long rock front of mudflow in the oreo shown in figure 11. The width of the flow is opproximotely eight feet. The smooth chonnel sides ore buried snow.

mud and rock and frequent chunks of snow, followed by a slurry of mud which passed progressively into muddy water (figure 13). The trailing muddy water tended to flush finer–grained loose debris from the channel, leaving it clear with a rocky bottom. Between the passage of mudflow surges, there was a minor but nearly continuous flow of muddy water. At individual points of observation along the channel, a temporary diminution or cessation in the flow of water frequently, but not invariably, preceded the approach of another mudflow. Debris damming the upper channel caused temporary interruption of the flow of muddy water.

Except when cascading through the bedrock chute, the mudflows moved in a laminar or non–turbulent fashion. Individual clasts tended to remain in the same relative position in a flow, slowly rotating and occasionally disappearing or, if on the snout, occasionally toppling down the front. As the viscosity of the flow decreased behind the rocky material, where it consisted of a slurry, or debris–laden water, the flow became turbulent (figure 13).

Generally, the movement of individual mudflow slugs was neither steady nor continuous from inception to deposition. Most mudflows, particularly the smaller ones of the waxing stage, halted at one or more points while in transit. During these interruptions, muddy water commonly drained from the coarse rocky snout, leaving a steep, bouldery front 1 to 4 feet high and relatively free of interstitial fines (figure 14).

Figure 13. View of turbulent–flowing muddy water following a mudflow, above the bedrock gap during the mature stage. Note the line of the upper level of mud passing through two upper bushes deposited during the waxing stage and subsequently removed during the climactic stage.

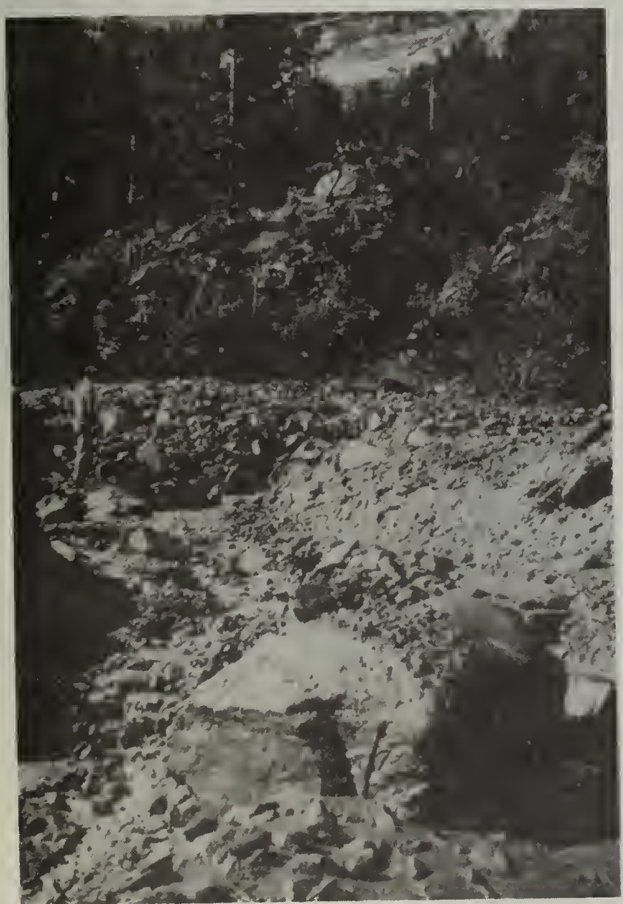

Figure 14. View southward toward bedrock gap up 9.5° reach, during the waxing stage. Note the front of stabilized large mudflow filling the shallow mudflow channel.

Where the flows were halted within the confines of the incised U–shaped channel, the debris slug was soon remobilized by being passed over by or combined with subsequent flows, particularly during the waxing and climactic stages. Where flows halted without effective side confinement, the debris slugs became stabilized and deflected later flows. This process was particularly noticeable during the waxing and waning stages, when it resulted in formation of a braided drainage pattern.

During the climactic stage, mudflows reached the gentler gradient of Heath Canyon fan and moved across its upper part where individual masses tended to merge, forming larger, more continuous flows in which the rocky snouts of former individual mudflows were recognizable only by short flow segments containing concentrations of boulders. The segments between boulder accumulations appeared visibly bimodal, with boulders interspersed in sandy mud (figure 15, 16, 17).

Frequency

During the waxing and waning stages, minutes to hours passed between the start of mudflows, which generally began in late morning and terminated in late afternoon due to diurnal variations in snow melt. During the climactic stage, mudflows began in early morning and continued after nightfall, continuing throughout the night on at least two occasions.

On the days during the climactic stage, slugs of debris descended the bedrock chute at intervals of 0.5 to 35 minutes, with a mean of 1.5 minutes for thirty measured interslug intervals. The frequency with

Figure 15. View of the mudflow immediately above area of principal deposition. Note the low front and its mixture of rocks and mud. The width of flow is approximately 12 feet.

Figure 16. View of the mudflow above the area of deposition. Here the width of flow is about eight feet.

Figure 17. View of the mudflow in the area of deposition. Here the width is approximately 50 feet.

which boulder accumulations or fronts passed the station on the fan during the climactic stage was 7 to 35 seconds, with a mean of 18 seconds for fifteen measured interfrontal intervals.

In the first two weeks of mudflow activity, relatively long intermissions (from several minutes to an hour or two) occurred between events that placed debris in the bedrock chute. During this stage, some individual events placing debris in the chute and their subsequent mudflows were clearly correlatable, even though some masses of debris that entered the chute were delayed there until they had absorbed sufficient water to flow down the channel. Later, as the meltwater stream–flow increased, the frequency with which debris reached the bedrock–chute commensurably increased. At this time, identification of individual masses of debris in the bedrock chute with specific mudflows farther downstream became less clear. During the climactic stage, sloughing and tributary mudflows continuously placed debris in the chute, where a mudflow or series of mudflows began as soon as sufficient water accumulated. During the climactic stage the point of initiation of mudflows migrated headward to an elevation of over 8,000 feet. Mudflows moving down the upper reaches of the channel commonly overrode and incorporated stationary slugs of debris that had calved from adjacent slopes.

During the waning stage, sloughing debris accumulated faster than it could be removed by the decreased amount of meltwater, and many mudflows moved relatively short distances down the channel. Some downward movement of debris continued after the mudflows stopped. As the surface of the landslide toe dried out, surface material began breaking loose and moving downhill into the steep drainage channel. There it formed a deposit of debris that will move again as part of another mudflow when rain or melting snow provides enough water to trigger the next cycle of mudflows.

Velocity

In the alluviated canyon bottom, mudflow velocities in the waxing stage were 4 to 5 feet per second. During the climactic stage, velocities in this reach ranged between 2 and 12.5 feet per second. On the fan a similar velocity range (2 to 12 feet per second) was measured, with a slightly slower mean velocity than in the alluviated canyon bottom. Flows with rounded snouts 8 to 12 feet across in this lower reach had velocity differences of 1 to 2 feet per second between the center and the slower–moving margins.

One flow was followed one mile downstream from the bedrock chute, and a mean velocity of 2 feet per second was measured. The 1941 mudflows had velocities averaging about 10 feet per second (Gleason and Amidon, 1941, p. 3–4).

Translatory Waves

In the flood control channel of the alluvial fan, translatory waves 1 to several inches in amplitude were generated during the climactic stage (figure 18). These waves moved down channel at approximately twice the speed of advancing mudflows. Most waves

Figure 18. Translatory wave in gravelly sand, view at the lower sample site.

were non-cresting, although a few crested, generally immediately upstream of the area of deposition of the mudflow. In contrast to minor waves generated by mud flowing over minor streambed irregularities, these translatory waves had the energy to travel several hundred yards and tended to move any halted boulder accumulations they encountered. Velocities measured for these waves ranged between 20 and 27 feet per second. Sharp and Nobles (1953, p. 552) reported similar waves produced during the 1941 mudflow activity.

Duration and Volume

Mudflows reached the observation station on the fan only during the climactic stage, commonly in a merged condition rather than as individual mudflows, making the duration and volume of individual mudflows difficult to estimate. These aspects are best estimated from the observations at the station in the alluviated canyon, where mudflows generally had durations of 1 to 9 minutes. Most had durations of from 2 to 4 minutes, but during the climactic stage a few lasted as long as 30 minutes. The flows which lasted 4 to 9 minutes were estimated to contain 200 to 900 cubic yards of debris each.

During the first five days of activity, an estimated 3,000 cubic yards of debris from all mudflows accumulated above the bedrock "narrows." After the snow dam was breached, at least 10,000 cubic yards of debris was deposited below the bedrock "narrows" and above the flood control channel. On the fan, the area of principal deposition, approximately 100,000 cubic yards of debris was deposited. Rearrangement of debris by the San Bernardino County Flood Control District to protect nearby homes precluded accurate measurement.

Thus, it is estimated that at least 110,000 cubic yards of debris (dry) was moved. Because of the admixed water in the mudflows, the total mudflow volume approaches 200,000 cubic yards.

Physical Properties

Forty mudflow and water samples were collected from May 9 to May 22, 1969. These samples were obtained by plunging a 4-inch-diameter can attached to a 6-foot pole into a flow. The sample was emptied into a double-layer polyethylene bag and sealed. Samples were collected in two locations (figure 6)—at the bedrock gap (upper sample site) and in the flood control channel (lower sample site), a short distance above the principal area of deposition. At each locality, samples were collected from the material immediately behind the rocky front (termed "gravelly mud" samples), from the boulder-free material in the terminal part of a flow (termed "sandy mud"), and from sediment-bearing water immediately following flows and interflow stream water. The diameter of the sampling can introduced a sampling bias for the coarsest parts of mudflows. The bouldery fronts could not be sampled (the can could not be forced into this material and clast sizes were greater than the can diameter). Those parts of flows that were sampled generally contained some clasts larger than the can. The samples, therefore, are not representative of the size distribution. Because the sampling method was consistent throughout the sampling period and at both stations, however, the data for comparable parts of mudflows at different times and stations are believed to characterize real differences and similarities (figures 19, 20, 21, 22).

Wet samples were weighed, dried and reweighed to determine the weight percent of rock. Specific gravity determined on dry debris gave an average value of 2.65. From these data the volume percent of rock and the specific gravity of the mud were calculated (tables 1–3). The weight percent of rock ranged between 12.3 and 88.2, the volume percent of rock from 51 to 75, and specific gravities of mud from 1.1 to 2.2. The mean specific gravity of gravelly mud samples from the upper site is 2.13 (a rock volume of 66 percent); samples from the lower site gave a mean value of 1.95 (a rock volume of 57.3 percent).

Table 1. Weight percent rock, volume percent rock, and specific gravity of mudflow samples, upper sample site.

Sample	*Weight % Rock*	*Volume % Rock*	*Specific Gravity*
1m	85.4	68.7	2.13
2m	83.5	65.6	2.08
3m	85.1	68.4	2.12
4m	86.0	69.9	2.15
5m	85.3	68.6	2.13
6m	85.0	68.2	2.13
7m	88.1	73.7	2.21
8m	88.2	74.6	2.23
9m	86.3	70.3	2.16
10m	85.1	68.4	2.13
11m	84.1	66.7	2.00
12m	85.2	68.4	2.13
1s	70.3	47.2	1.78
2s	62.5	38.5	1.63
3s	29.5	13.6	1.22
4s	79.0	58.7	1.96
5s	55.0	32.0	1.53

m = gravelly mud
s = sandy mud

Table 2. Weight percent rock, volume percent rock, and specific gravity of mudflow samples, lower sample site.

Sample	Weight % Rock	Volume % Rock	Specific Gravity
1m	78.0	57.4	1.94
2m	82.3	63.7	2.05
3m	80.7	63.0	2.04
4m	82.2	63.5	2.05
5m	78.7	58.2	1.96
6m	67.3	43.7	1.72
7m	73.7	51.3	1.85
8m	83.5	65.6	2.08
9m	82.1	63.4	2.05
10m	67.3	43.7	1.72
1s	75.2	54.4	1.90
2s	74.1	51.9	1.85
3s	55.4	31.9	1.53

m = gravelly mud
s = sandy mud

Table 3. Weight percent rock, volume percent rock, and specific gravity of water samples, both sample sites.

Sample	Weight % Rock	Volume % Rock	Specific Gravity
1	28.7	13.2	1.22
2	41.7	21.3	1.35
3	61.0	37.2	1.61
4	49.2	26.8	1.44
5	30.1	14.0	1.26
6	46.7	33.0	1.54
7	13.3	5.4	1.09
8	12.3	5.1	1.08
9*	80.7	61.2	2.01

* Included several rocks apparently moving as bed load and not as suspended material.

Grain Size

The dried samples were mechanically analyzed and cumulative size distribution curves were prepared. The cumulative curves for gravelly mud (figures 19, 20) are of particular interest. Gravelly mud samples from the upper site have a median grain size of about 4 mm; the median grain size for the lower site samples is approximately 1 mm. This decrease may be partly an artifact due to vertical redistribution of coarse material within the flowing mass.

Three processes could bring about an actual decrease in the median grain size of an entire flow — the fragmentation of larger clasts as they travel downstream, dilution by the addition of finer grained material, or removal of the coarser grained fraction by deposition in the channel. However: (1) samples from the upper site are approximately 1,800 feet from their point of origin, those at the lower site are approximately 6,900 feet from their point of origin, and the short distance of transport in a matrix material of such high specific gravity and viscosity suggests that extensive fragmentation of clasts is unlikely; (2) visual examination of the material through which the deep channel was cut shows no "lag" concentrations of coarse debris from which fine-grained material was selectively eroded; and (3) the progressive channel deepening precluded selective deposition of the larger clasts in that reach. In addition, field observations showed that there was no net deposition of the coarser grained fractions in the channel above the lower sample site during the period that it was reached by flows.

The decrease in median grain size may, therefore, be only apparent due to sampling procedure or rearrangement of material within flows as they moved down channel. Analysis of the sampling technique suggests that the most likely systematic bias deficiency of larger clasts should tend to reduce rather than increase differences in the means from the two sites. In-flow sorting could occur vertically and/or longitudinally down channel. Comparison of median sizes of material in sandy mud in the terminal parts of flows in each of the sample sites indicates no noticeable longitudinal sorting. Thus, it is likely that grain size decreases because the flow is vertically sorted as it moves down channel while the stream gradient decreases nearing a site of deposition. The material at the upper sample site may be unsorted, normal graded, or reverse graded. Apparent diminution in grain size at the lower sample site could thus be due to normal grading of an unsorted material, intensification of a normal graded material, or normal grading of a previously reversed graded material. No unequivocal answer is apparent from existing information. Unfortunately, it is clear that the samples are not representative of the entire vertical section of the sampled part of a flow.

The sorting index for the samples from the upper site ranges from 3.4 to 4.2; for the samples from the lower site the range is 4.8 to 5.2. This suggests that the material becomes increasingly unsorted down channel, although it may be attributable to the previously discussed problems with obtaining samples and the inferred variation in sorting of flows in the flood control channel. Size distribution histograms (figure 23) indicate that no more than half of the gravelly mud clasts at the upper site were sampled, giving rise to the relatively low sorting index, whereas the flow samples collected from the lower site had less coarse material.

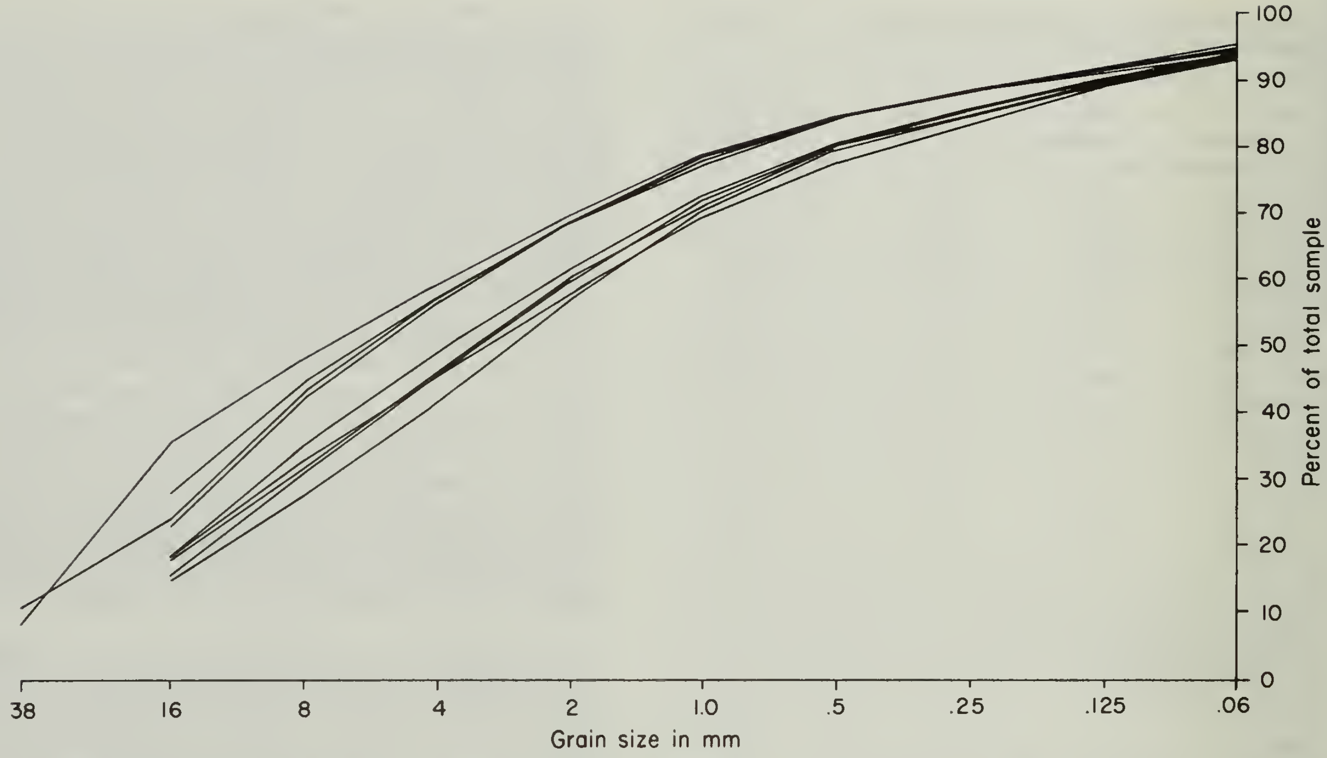

Figure 19. Cumulative curves for gravelly mud samples from the upper sample site.

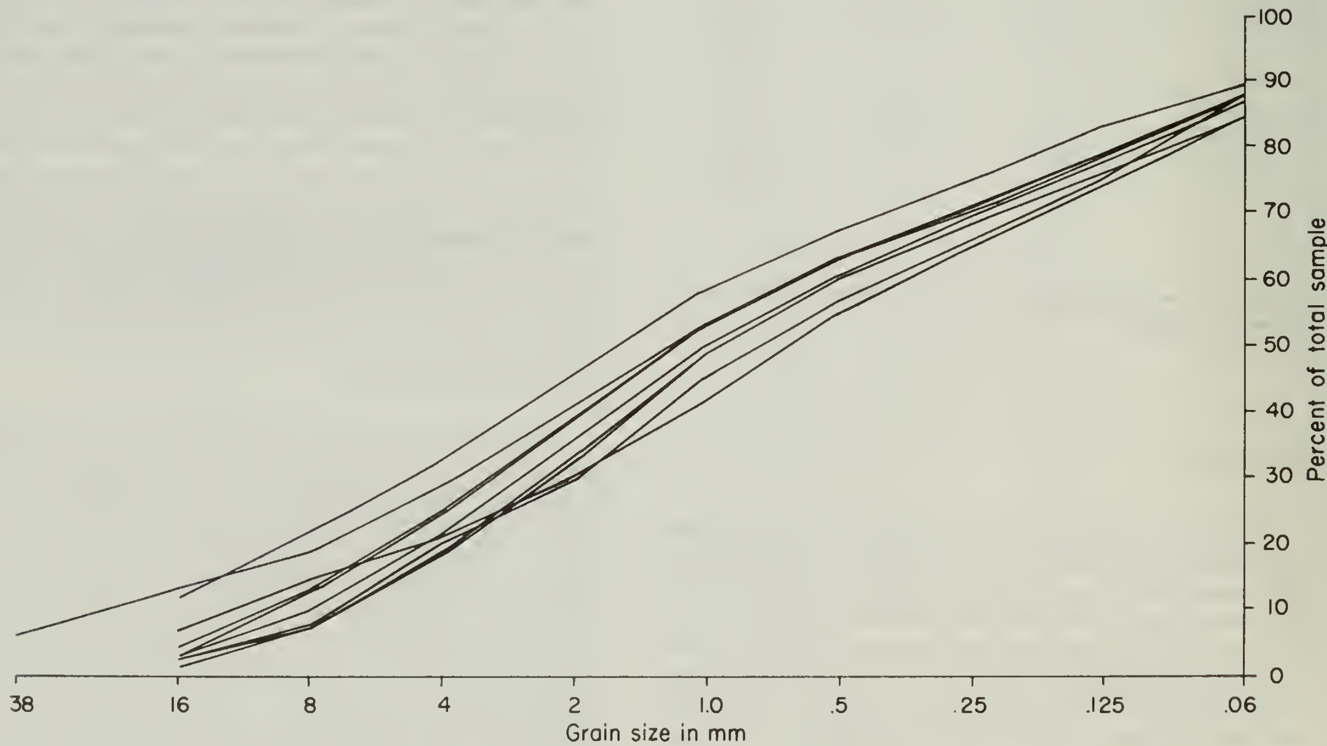

Figure 20. Cumulative curves for gravelly mud samples from the lower sample site.

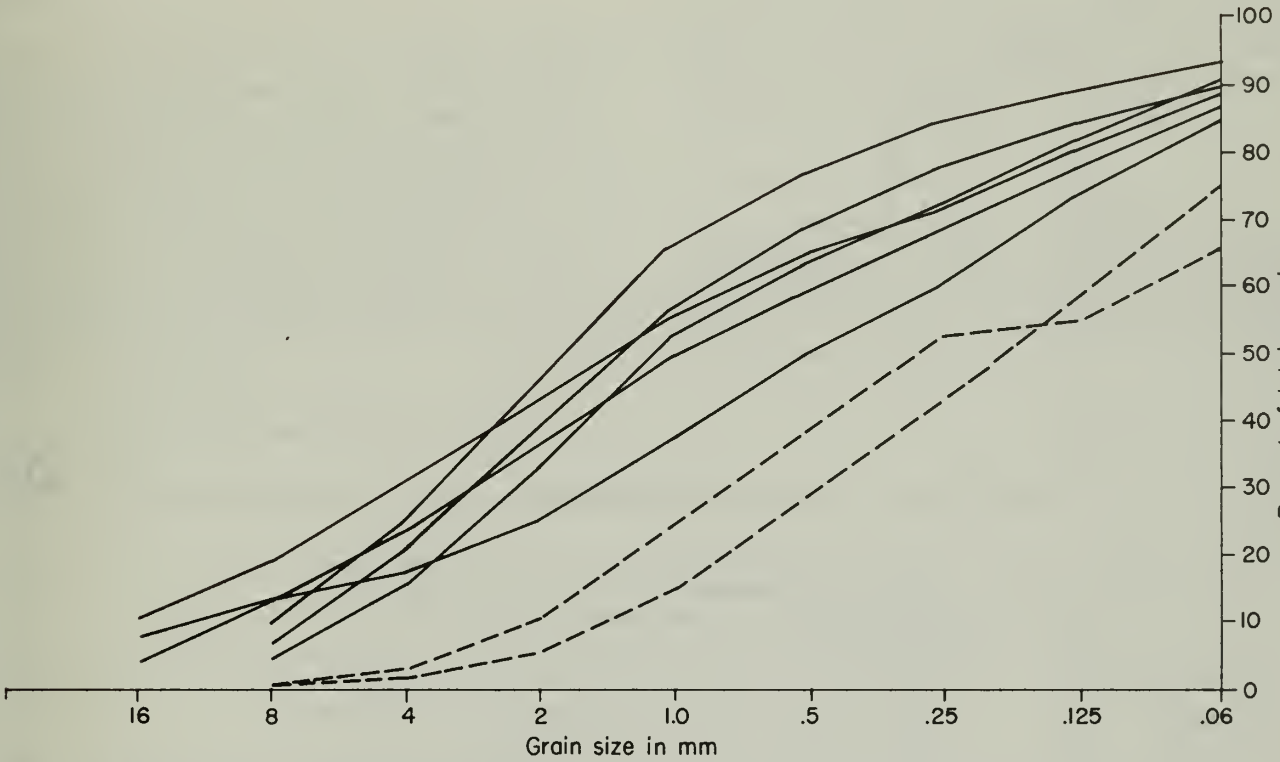

Figure 21. Cumulative curves for sandy mud (solid lines) and water (dashed lines) samples from the upper sample site.

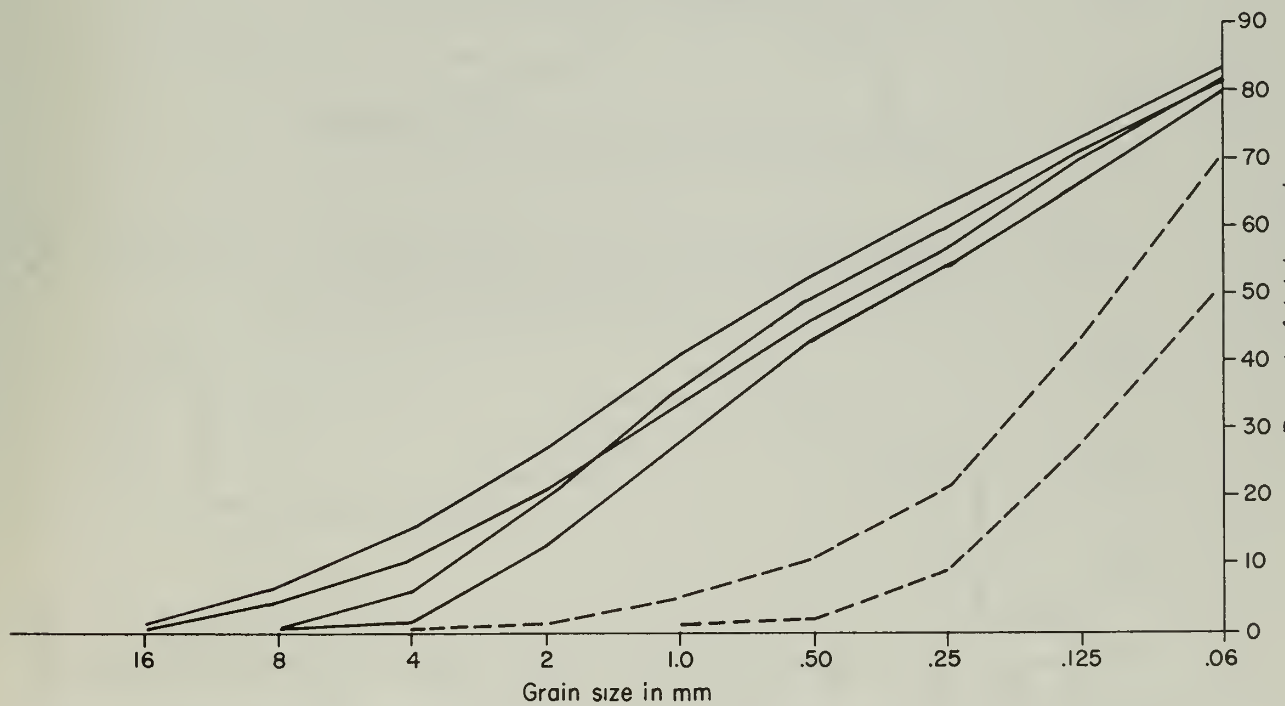

Figure 22. Cumulative curves for sandy mud (solid lines) and water (dashed lines) samples from the lower sample site.

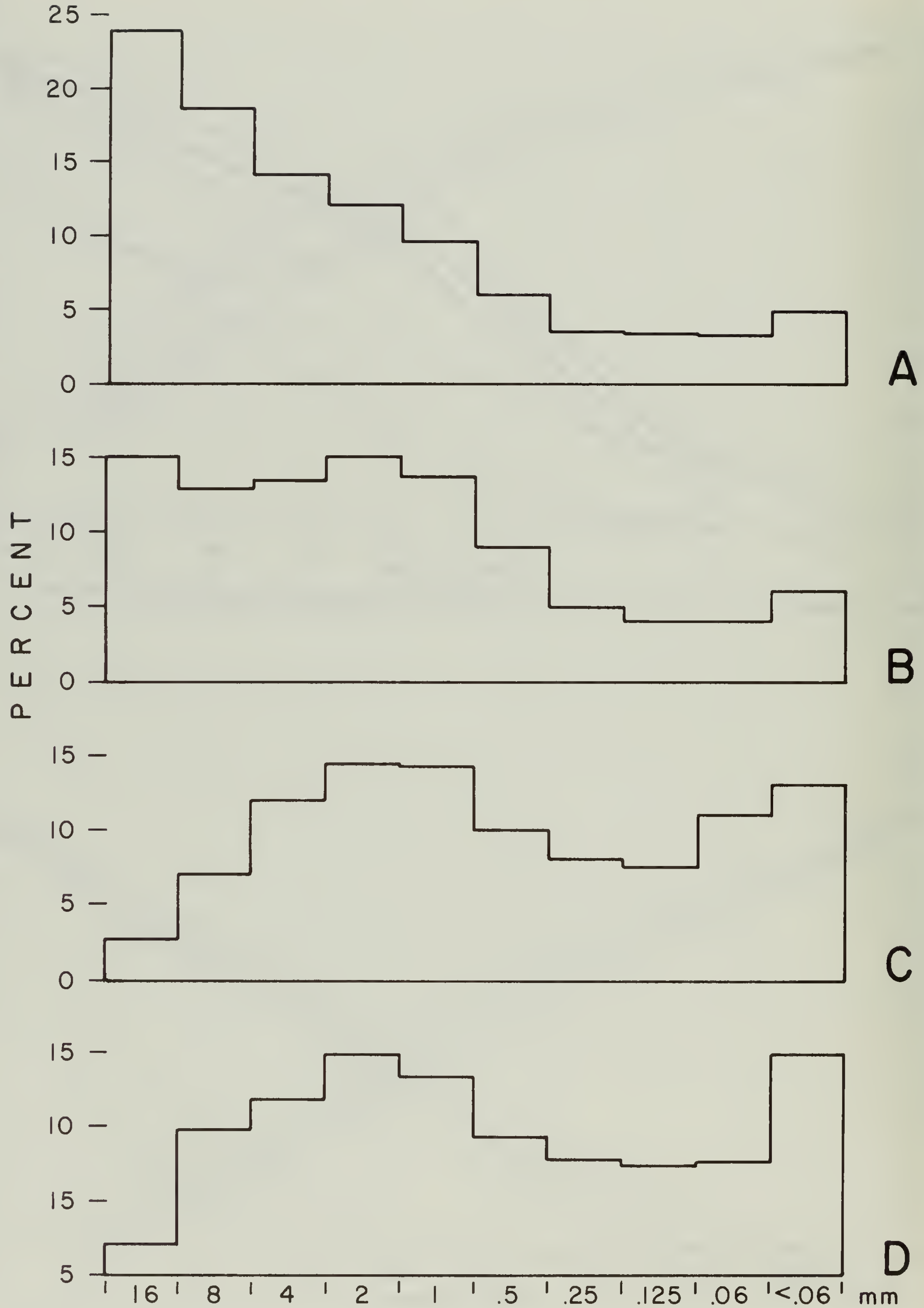

Figure 23. Histograms of size – frequency distribution for mudflow samples from upper sample site A and B and lower site C and D.

Viscosity

Data collected on mudflows and mudflow samples allow estimation of viscosity of the mudflow material. Calculations of Bingham viscosity (Johnson, 1970, Chapter 14) indicate viscosity immediately behind the rocky snouts of the flows to be approximately 8×10^2 to 10^3 poises; in the next mud/rock mixture $4 - 6 \times 10^2$ poises; and in the turbulent flowing water following a mudflow approximately one poise. Johnson (1970, p. 813) calculated the Bingham viscosity for a flow at Wrightwood on May 20, 1969, to be approximately 7.6×10^2 poises.

Sharp and Nobles (1953, p. 552–553) calculated Newtonian viscosities of the 1941 mudflows to range from 2.1×10^3 to 6×10^3 poises. Using their formula, viscosities for the 1969 mudflows range from about 1×10^2 to 6×10^4 poises.

Entrained Air

The samples from stabilized mudflows collected at the lower sample site, with the size fraction of 2 inches removed, were tested for entrained air content. Both samples had a 0.3 percent air content (J.R. Townsend, 1969, personal communication).

CONCLUSIONS

The debris placed in Heath Creek Canyon by the 1967 landsliding was only in small part removed by the 1969 spring mudflows. There is sufficient debris remaining in the canyon to produce several episodes of mudflows comparable to those of 1941 or 1969. Assuming these future flows are confined to the flood control channel, the principal site of mudflow deposition will be the same as where the bulk of deposition occurred in 1969.

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